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STUDY OF THE 4-DAY RETROGRADE ROTATION OF THE EXTERNAL CLOUD LAYER OF VENUS

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STUDY OF THE 4-DAY RETROGRADE ROTATION OF THE EXTERNAL CLOUD LAYER OF VENUS

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ABSTRACT. We review briefly photographic as well as spectrographic observations which have allowed us to prove and confirm the retrograde rotation of about 4 days of the external cloud layer of Venus. Certain configurations visible in ultraviolet light -- in particular two spots having the shape of a horizontal Y -- seem permanent, and we can establish their cartography. But the observations suggest that high-lying clouds cover these configurations from time to time. An examination of the displacement of the equatorial spots during time intervals of several hours furnishes an instantaneous synodic rotation period somewhat larger than 4 days for the permanent spots. The synodic period is shorter for the variable spots. The observations of the periodic return, at the subsolar point, of the equatorial Y shaped configurations, suggest that the mean rotation period of these spots is remarkably constant and almost equal to 4 days. This period increases considerably when the spot latitudes are greater than ±6°. Ephemerides have been calculated for the years to come.

The agreement of findings obtained in the United States as well as in the Soviet Union using the decimeter wave radar echo method suggests ascribing to the solid sphere of Venus a period of sidereal rotation on its axis equal to 243 days in a retrograde direction, in this way bringing to 117 days the duration of the solar day on Venus. Our objective was to describe and analyze our own observations made with violet and ultraviolet light. These observations were taken in relation, not to the solid surface of Venus, but to the visible part of the opaque cloud layer surrounding the planet. /338*

Discovery of the Approximate 4-Day Retrograde Rotation of the Clouds

It is known that the spots of the cloud surface of Venus are only clearly detectable -- barring exceptional cases -- when using short wavelength light. This was shown by Ross as early as 1926 by means of a series of photographs

*Numbers in the margin indicate pagination in the foreign text.

taken in the ultraviolet range at the Mount Wilson Observatory. Such photographs can form the basis for investigations concerning whether or not there is an aggregate movement of these spots and whether this movement corresponds to a rotation. As far as Ross was concerned, he was only able to conclude that, providing a rotation did occur, its period was longer than 3.5 days. /339

On the recommendations of H. Camichel, one of us (Ch. B.) began in 1957 a program of photographic observations of Venus using short wavelength light. This program was directly inspired by the one carried out by Ross 30 years before. The instrument used was a small reflector with a 26 cm aperture located in Brazzaville (Congo). The photographs were taken with a very fine grain, high-contrast 35 mm film (Kodak Microfile) through a Wratten 34 violet filter (transmission maximum: 4200 Å). The equivalent focal distance was 10 m and the exposure times ranged between 1/5 and 1/10 s. Begun on 28 August, the photos showed on that particular day a dark strip perpendicular to the line of cusps bisecting Venus. On 29 and 30 August, the equator of Venus was clear and the cusps obscured. On 1 September, or 4 days after 28 August, the dark equatorial strip reappeared. It was seen again on 5, 9 and 13 September whereas on the other days the equator of Venus remained clear.

Such appearances suggested a 4-day rotation period (although still no direction specified). H. Camichel, when informed of this discovery, established without difficulty the 4-day recurring phenomenon on photos he had taken in 1953 at the Pic du Midi. In 1962 this recurrence was again confirmed on many occasions (when the images were good) on photos taken at Brazzaville using the same telescope but this time with ultraviolet light supplying a higher contrast for the spots (UG2 filter, transmission maximum: 3800 Å, equivalent focal length: 15 m). Some stereoscopic pairs made up from photos taken at half-hour intervals showed (with a considerable lack of precision owing to the smallness in size and blur of the images) a movement of the spots in the retrograde direction at the rate of about one revolution per 4-day period. It therefore certainly appeared to be a matter of a rotation of the clouds and not of recurrent atmospheric phenomena taking place on the spot at 4-day intervals as had been suggested in the beginning by some astronomers who were reluctant to involve synchronous rotation as a basis.

Furthermore, the aggregate of all these photos revealed the existence of a Y-shaped horizontal cloudy spot which can be observed for long periods and comes back, in this event, every 4 days to a position facing the earth. The shaft of this Y extends over more than 100° to form the dark equatorial strip described above. As for the two upper branches of the letter, forking on either side of this strip towards the North and South temperate latitudes, they are the origin of the appearances observed on very low-resolution photos when the equator of Venus is clear and the cusps obscured.

In addition, the synoptic maps obtained by superimposing on a Mercator projection survey all the details successively photographed during an elongation did not reveal any detail when the assumption was made that the cloud layer rotated in a counter-retrograde, or clockwise, direction whereas, when the opposite assumption was made (retrograde or counter-clockwise direction), they always showed the Y-shaped formation with attendant reinforcement.

Direct Proof of the 4-Day Retrograde Rotation

However significant as these findings were as discussed above, they were not as yet finally conclusive. The resolution of the photos used as a basis was too often insufficient and, especially, no successive series of images were made for several hours at a time in order to enable a direct demonstration of the progressive movement of the spots in a retrograde direction at a /340 rate of about one revolution every 4 days.

Within the scope of the International Astronomical Union (IAU), A. Dollfus undertook in 1962 to organize a worldwide campaign for photographic observations of Venus using ultraviolet light. The observatories involved were distributed quite uniformly in longitude throughout the world in such a manner as to obtain images coming sequentially in intervals of several hours at a time. Several great observatories participated in this campaign and a great number of good quality photos were added to the files. Deserving special mention are those photos taken by G. Herbig (Lick, 300 cm reflector), B. A. Smith (New Mexico, 30 cm reflector), H. Camichel (Pic du Midi, 105 cm reflector), etc. The comparison which we personally made with some of these pictures -- more particularly those taken on 23 July 1962 at 0100 hrs GMT (New Mexico) and at 0322 hrs GMT (Lick) -- gave us confirmation that it undoubtedly involved a progressive movement of the spots in the retrograde direction. New photos were obtained in 1964 -- more particularly those taken on 12 March at 0055 hrs (New Mexico), 1855 hrs (Pic du Midi) and 2400 hrs (New Mexico). They led us to the same conclusion. Nevertheless, this result remained controversial.

It was only during morning elongations of spring and summer that the authors, using the 105 cm reflector of Pic du Midi, were able for the first time to show a decisive and direct photographic proof of retrograde rotation of the entire cloud layer of Venus with a period of about 4 days. This was done using a series of snapshots scaled over several hours in total and taken under identical conditions from sunrise up until transit of the sun across the meridian and even beyond.

Up until this time, photographic observations of Venus made at a given observatory were more often than not limited to short time intervals centered each day on the time of sunrise and sunset. Indeed, when the planet is very low on the horizon, its appearance is generally affected by a strong perturbation. The same situation is true when it is high, in broad daylight, as a result of heating by the sun of the opening of the cupola's hatch and the end of the instrument's tube. Furthermore, the blue of the sky creates in this case a considerable background hazing quality which greatly decreases the contrasts. Some tests were tried, however (Slipher, 1935; Dollfus, 1948), but they neither supplied conclusive results nor gave the slightest indication of movement on the part of the Venusian spots.

Owing to the atmospheric quality at the Pic du Midi, we were able to have the advantage of images, often acceptable and occasionally excellent, which had been taken with the target still quite low above the horizon. The hot air eddies in broad daylight were limited to the maximum by ventilating the cupola on a permanent basis and only working in short successive periods between which we rotated the hatch to the opposite direction from the sun so as to avoid even a short period of heating up of the telescope aperture. This heating had been found to be harmful to any observation when it lasted for more than a minute. A parasol, fastened to the cupola on one of the sides of the hatch, was used various times but it did not enable doing away with rotating the hatch to the opposite direction from the sun during periods of observation since it was also itself prone to heating problems and created eddies. Finally, a long tube darkened on the inside and centered on the instrument's optical axis at the Cassegrain focus, only allowed passage of beams limited by the contour of the secondary mirror reducing in this way the haze produced by the sky's background.

Most of the photos were taken through a UG2 ultraviolet filter with an equivalent focal length of 35 m (Ch. B.). Some images were made through a Wratten 34 violet filter with a focal length raised to 65 m (P.G.). We usually used PF Ilford 35 mm film with a fine grain and high contrast. Some photos were taken in ultraviolet, furthermore, after sunrise using Kodak Microfile whose contrast is still greater than that of Pan F. This was done so as to make up for the loss in contrast of images made in broad daylight. The exposure times were scaled between 1/20 and 1/5 sec. On most negatives the /341 spread to the limb reached 1" or 2" but was reduced to 0.5" in the best cases. Some of the series obtained in July were of high quality and remarkably homogeneous.

It was possible to ascertain that the movement of the spots was observed effectively and without ambiguity in all series obtained. The longest of the latter (24 July) showed the retrograde rotation of the Y during 10 hours at one stretch. (The last picture of this series was forwarded to us by B. A. Smith as well as the last image of the series of 25 July.) It undoubtedly concerns an aggregate rotation being carried out as a first approximation around an axis normal to the orbital plane. The linear movement is maximum at the center of the disk and the spots can be distinctly seen in the best series flattening out under the effect of the perspective as they come closer to the limb. In addition, it can be noted that the cloud configurations preserve the same general shape for several hours at a time although they could, in some cases, vary slightly in detail. The comparison of photos made both in violet and ultraviolet light confirms the reality of these variations. Finally, measurements made with each series supplied the corresponding instantaneous rotational speed. As we shall see below, the values found are rather scattered but their average corresponds to a period a little less than 4 days.

New series of ultraviolet photos have been obtained since that time by one of us (Ch. B.) using the 105 cm reflector of Pic du Midi both in 1967 and 1968 (evening elongations). In every respect they allowed configuration of the conclusions derived from the observations of 1966. For his part, B. A. Smith carried out in 1967 in New Mexico a considerable series from which he was able to show, just as we had done a year earlier, the progressive movement of cloud formations in the retrograde direction with the measured speed corresponding to one revolution in 4.7 days (sidereal rotation).

Finally, it happened that at the time when we were making the above-mentioned observations, B. Guinot was obtaining results similar to ours at the Haute-Provence Observatory by a completely different method (measurements of radial velocities in the visible part of the spectrum in various regions of the Venusian disk using an interferential spectrometer). The measurements of Guinot, just as did our measurements, dealt with evening elongations (1964, 1965), as well as morning elongations (1966). They supplied significant variations which were always in the same direction. Although these variations are interpreted as having their origin in a total rotation of the cloud mantle around an axis perpendicular to the orbital plane, they suggest a mean sidereal period of 4.3 ± 0.4 days (weighted value) in the retrograde direction.

For the reasons above, the phenomenon is no longer in doubt. All that remains is for us to study it in detail by using the vast documentation now available to us.

Planisphere of the Recurrent Cloud Formations of Venus

The horizontal Y-shaped dark spot which we have discussed above is not always available for observation. Sometimes it can be seen appearing opposite the earth about every 4 days whereas, at other times, it cannot be seen clearly. When it has been lost from sight for a period of time, it always reappears, as we shall soon see, after a whole multiple of 4 days (plus or minus a fraction of a day). Finally, although it can be seen most clearly, in violet light, it is likewise sometimes possible to make it out in visible light as has been found on a sketch by Danton, dated 10 November 1926, or two sketches by Lowell, dated 14 April 1903, and on one sketch by Rudaux, dated 25 March 1903.

One point was still, however, left in the dark up until 1966. For, although this Y was most often seen about every 4 days, the time interval was occasionally 3 days or even 5 days.

The reason for this fact is, in our opinion, as follows. There is a second horizontal Y located at almost exactly 90° from the first one in longitude and whose shape is, furthermore, slightly different. On photos taken in /342

1953, Camichel already believed he had revealed two Y-shaped structures located at 90° from each other. However, the poor quality of the pictures did not permit final substantiation of this finding. The 1966 photos completely confirmed the interpretation of Camichel at the same time providing more specifications. On the first images of the 24 July series, beginning at 0344 hrs, the Y is perfectly visible halfway between the central meridian and the limb. On the last images, taken at 1120 hrs and at 1245 hrs, it disappeared past the limb. On the following day, 25 July, a similar series showed an approximately like formation slightly displaced in latitude but occupying the same successive positions in longitude as the day before. The quality of the pictures allowed showing for the first time some specific differences between the shapes of these two Y structures. The second one is more rounded off than the first one and a dark strip can be seen between the two branches giving the approximate appearance of the letter Psi. On 12 July, or three times 4 days before the 24th, the true Y could be recognized on the photos. On 9 July, or 3 days before the 12th, or again four times 4 days before the 25th, the Psi formation, with a rather hazy northern branch in this case, was recognized quite easily. Starting from these considerations and supplied with sufficient criteria to be able to discriminate between Y and Psi, it was now possible to identify the Psi on many previously taken pictures. The mean period of recurrence of transit of these spots was thereby brought back to 4 days and never to 3 or to 5. Let us point out in this respect that a Y-shaped formation can be seen on a sketch by Lowell dated 22 March 1903 which is previous by 3 days to the sketch by Rudaux mentioned above. This suggests, therefore, that this formation is the Psi and that the Y seen on the sketch by Rudaux is the "true" Y.

Thus, it appears that the Y is not the only recurrent cloud formation on Venus, but that a second spot, quite similar but slightly different in shape, can likewise frequently be observed, offset in longitude by 90° with respect to the first one. This comment led us to again examine all of the best photos in order to investigate whether, behind the great variety of shapes offered by the spots seen outside of the Y and Psi transits, other recurrent structures were not to be found. Such structures were indeed identified and the synoptic map which we show here summarizes the total of our observations. This map shows to some extent the "average" appearance of the cloud configurations of Venus with ultraviolet light given, of course, that this appearance could be found to be more or less changed at any instant just as if high atmospheric hazes had become interposed leading then to an attenuation of the spots and occasionally even to creation of transitory phenomena with unpredictable shapes.

Measurements of the Instantaneous Speed of Cloud Spots Close to the Equator [1]

These measurements were made using the best series of 1966 and 1967. We added to them some very short series from 1965.

The method used for data reduction is the following. The best negatives are selected on an approximate hourly basis. Each one of these negatives is enlarged with 10 copies on soft-grade paper (Venus' diameter: about 30 mm). Such images show the spots with a slight contrast which would make photomechanical reproduction difficult. Nevertheless, they have the advantage of showing them totally over the whole visible part of the disk, in spite of the darkening at the terminator which is itself reduced owing to use of soft paper.

A system of rectangular axes whose origin passes through the center of the disk of Venus is plotted on each photo by a dry-point etching technique, one of these axes being parallel to the line of cusps. In order to define the position from the center of the disk, a preliminary plot is made, still /343
using the dry point technique, of a circle whose diameter is equal to that of the image, this circle following as closely as possible the contour of the limb. The coordinates of the spots will be measured in this system.

It is advisable to note that the diameter of photo images of Venus -- even when these images are correctly exposed -- is systematically a little smaller when it concerns images taken at night rather than by day. This is owing to the existence of the sensitivity threshold which does not allow the emulsion to record the light spread out on the black background of the sky at a limited distance from the limb since this light is too weak. The result is that the photographic profile differs from the true photometric profile. In broad daylight, on the contrary, the light from the background of the sky is

1. We make an implicit assumption here that the equator of Venus merged with the orbital plane. (It, of course, concerns the equator relative to the atmospheric envelope in rotation.) Such a hypothesis is justified as a first approximation as will be seen during this chapter.

added to the light spread out beyond the limb allowing the latter to expose the emulsion which then more correctly reconstitutes the true photometric profile. We should therefore use, for the diameter of circle which we are plotting on the positive printings, that diameter of the images of Venus taken in broad daylight. We would introduce an error into the measurement of the coordinates of the spots by acting otherwise. One of us (Ch. B.), furthermore, took care to confirm, by means of direct measurements of the focal distance of the telescope, that the diameter thus measured was actually the true diameter of the planet.

When the Y or Psi spots can be seen, the intersection of their branches supplies the reference point for measurement of the rectangular coordinates in the plane of the image. These coordinates are subsequently transformed into latitude and longitude with respect to the subsolar point. When the photos show neither the Y nor the Psi, aim is taken on the apparent center of gravity of the best defined spot.

When the series includes exploitable photos for periods of at least one hour, which is practically always the case, it is possible to graphically compute the synodic speed of rotation by plotting the dates in hours and minutes of each negative as abscissos and the corresponding longitudes of the reference point as ordinates. In order to reduce errors arising owing to lack of precision in measurement plotting, each longitude is measured independently for each one of 10 printings obtained from the same negative and the average is taken of these 10 measurements. The slope of the straight line passing best through all the points obtained in this way gives the average speed of rotation during the period of time under consideration. This speed can be termed instantaneous taking into consideration the fact that the total angle of rotation on which the measurements are made is only a small fraction of 360°.

It is noted that, in general, the movement of the reference points is made perpendicularly to the line of cusps, allowing for slight measurement errors. Nevertheless, it happens that this law is not completely confirmed. On the other hand, there may frequently be observed abrupt variations in the speed of the reference points between the beginning and the end of one series to the extent that the latter is extended over a sufficient period of time. These variations are clearly greater than measuremental errors and probably arise from local turbulence in the Venusian atmosphere. The result is that the measured speeds are all the more representative of the instantaneous speeds of average rotation with increasing length of the period of time covered by the series. We can, therefore, award a weight to the measurements with this weight being proportional to the length of observation.

Thirty series have been processed in this way. With some of them, two and even three reference points were measured. The results are listed in Table 1 and shown in the histograms of Figures 1, 2 and 3.

a. The histogram of the 10 series showing the Y and Psi in the vicinity of the equator (Figure 1) shows a marked maximum around the speed - 100 m/s. The weighted average of the speeds is 105 m/s. The histogram can /345
be shown in a second way by using as abscissos the absolute values of the measured speeds and the weighted average of these speeds (Figure 2). The plot produced recalls quite well a bell-shaped Gaussian semi-curve and it is therefore possible to determine the probable deviation ± 11 m/s of the speeds around the weighted average.

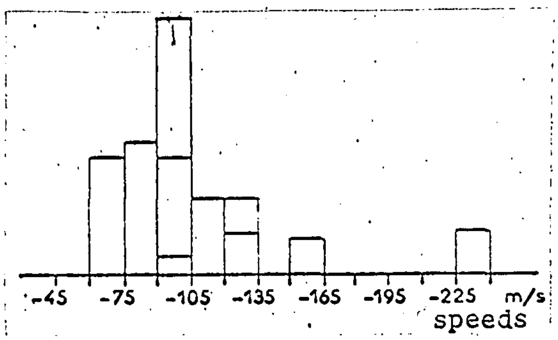

Figure 1. Histograms of instantaneous speeds of equatorial Y and Psi. The heights of the rectangles are proportional to the weights awarded the measurements.

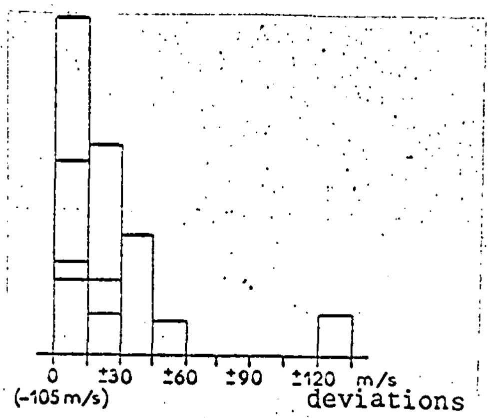

Figure 2. Histogram of deviations between the instantaneous speeds of equatorial Y and Psi spots and the weighted average of these speeds. The plot produced calls to mind a Gaussian distribution whence it is possible to deduce the probable deviation of the speeds ± 11 m/s in the vicinity of the weighted average - 105 m/s.

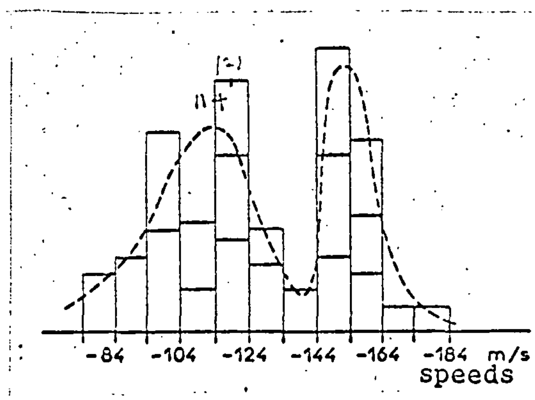

Figure 3. Histogram of the instantaneous speeds of equatorial spots other than the Y and Psi spot.

TABLE 1. INSTANTANEOUS SPEEDS OF ROTATION OF EQUATORIAL CLOUD FORMATIONS /344

Date	Duration	Reference Point	Speed in m/s	Latitude	Weight
8/9/65	1h00	Y	-90 ± 59	6.0°	1
13/9/65	1h53	Psi	-157 ± 61	2.4	2
12/4/66	2h31	Psi	-127 ± 86	0.8	2.5
20/5/66	3h46	Spot	-129 ± 23	-	4
21/5/66	2h14	Spot	-127 ± 46	-	2
22/5/66	4h18	Spot	-147 ± 41	-	4.5
Id.	Id.	Psi	-110 ± 21	6.2	4.5
24/5/66	3h42	Spot	-154 ± 49	-	3.5
26/5/66	2h43	Spot	-110 ± 50	-	2.5
28/5/66	6h15	Spot	-96 ± 15	-	6
2/6/66	4h07	Spot	-108 ± 54	-	4
9/7/66	6h04	Psi	-98 ± 30	0.6	6
12/7/66	8h24	Y	-92 ± 24	4.1	8.5
13/7/66	6h10	Spot	-150 ± 37	-	6
16/7/66	3h42	Spot	-160 ± 56	-	3.5
23/7/66	4h35	Spot	-157 ± 36	-	4.5
24/7/66	8h02	Y	-88 ± 50	2.5	8
25/7/66	7h01	Psi	-68 ± 42	4.4	7
26/7/66	5h56	Spot	-102 ± 24	-	6
21/3/67	2h08	Y	-133 ± 75	3.5	2
1/12/67	1h32	Spot	-171 ± 93	-	1.5
2/12/67	1h35	Spot	-181 ± 88	-	1.5
Id.	6h30	Spot	-147 ± 80	-	6.5
3/12/67	5h21	Spot	-120 ± 52	-	5.5
Id.	2h39	Spot	-135 ± 46	-	2.5
4/12/67	4h54	Spot	-121 ± 61	-	5
Id.	4h27	Spot	-124 ± 51	-	4.5
6/12/67	4h32	Spot	-93 ± 32	-	4.5
Id.	3h41	Spot	-79 ± 69	-	3.5
Id.	2h20	Psi	-229 ± 99	4.5	2.5

The value thus determined of the diurnal equatorial speed of equatorial Y and Psi spots:

$$-105 \pm 11 \text{ m/sec}$$

probably corresponds to a complete revolution in 4.25 ± 0.44 days (synodic rotation) provided the rotation remains constant during the complete rotation.

b. The 20 series showing equatorial spots other than Y and Psi provide a histogram (Figure 3) showing two very clear maximum values, one in the vicinity of -110 m/s and the other in the vicinity of -155 m/s. The first maximum value is related to cloud formations which rotate appreciably at the same speed as Y and Psi and which are probably located at the same level in the atmosphere. The second maximum value is related to much faster moving formations (one revolution in 2.8 days).

This fact should be reconciled with the existence already pointed out of hazes which can occasionally hide Y and Psi spots and which we have assumed for this reason to be located at a higher level than the latter spots. Plate IV shows the very fast retrograde rotation of such hazes above the Y and Psi spots. Our observations and measurements therefore appear to point out a very appreciable increase in the speed of atmospheric rotation at a specific altitude above the relatively dense layer supporting the recurrent cloud formations.

It is advantageous to compare the whole of these results with those of Guinot which were obtained by measurement of radial velocities in different regions of the disk and with those of Smith which were obtained like ours by measuring the movement of ultraviolet spots in several hours. Let us recall that Guinot finds an average period of instantaneous sidereal rotation equal to 4.3 days whereas Smith has found a period equal to 4.7 days. Translated into synodic rotation, these periods become respectively equal to 4.2 and 4.6 days.

Insofar as the measurements of Guinot are concerned, they essentially involved regions in the vicinity of the cusps and center of the disk, on one hand, and regions of the limb near the terminator, on the other hand. They supply, therefore, the instantaneous equatorial speed of the cloud mantle just like our own measurements. Nevertheless, they were made in orange light and should probably be referenced to layers appreciably deeper than those to which access is possible by observation in ultraviolet light. Also, it can be anticipated that they reveal a speed rather less swift than that which we find, on the average, for the various formations which formed the subject of our measurements. This was effectively true which would tend to confirm our interpretation according to which the speed of rotation decreases when the atmosphere is penetrated.

As far as our disagreement with Smith is concerned, we suggest that it rests in the fact that, conversely to this author, we have only measured the instantaneous speed of cloud formations located not far from the equator. We shall see, indeed, in the following paragraphs that the Y and Psi spots revolve more slowly when their latitude exceeds 6°.

Study of the Periods of Recurrence of Equatorial Y and Psi Spots

It is quite clear that observation of the successive transits of the Y and Psi spots across the subsolar point will enable us to discover the true duration of the synodic rotation of these spots and to determine whether or not this duration is constant on the average.

Preliminary measurements have shown us that such an average period, very close to 4 days, appears possible to define. However, systematic deviations were observed when the centers of the Y and Psi spots deviated considerably /346 from the equator. Beginning from this observation, we have first of all removed all photos in which the Y and Psi spots are located more than 7° from the equator. Among the photos remaining, we then selected those allowing discrimination to be made between the Y and Psi spots. Thus, we are certain, for example, that it was undoubtedly the Y spot which transited the subsolar point on 18 June 1962 for a second Y -- which is accordingly the Psi spot -- transited the subsolar point in turn 24 hours later.

Table 2 supplies dates for the photos used during the elongations of 1927, 1938, 1948, 1953, 1962, 1964, 1965, 1966, 1967 and 1969. We have in- /347 serted three old visual observations (two sketches by Lowell mentioned above which show the Y and Psi spots as well as one sketch by Danjon, likewise mentioned above, and on which the Psi structure is perfectly recognizable). These sketches will only be used in the capacity of supplemental and non-essential documentation.

TABLE 2. CLEARLY DEFINED RECURRENCES OF EQUATORIAL Y AND PSI SPOTS

PSI

Intervals	Dates
	22/3/1903
8633.76	
	10/11/1926
379.09	
	23/11/1927
3847.72	
	7/6/1938
3560.15_5	
	6/3/1948
2013.40	
	9/9/1953
3203.00_5	
	19/6/1962
7.75	
	26/6/1962
883.20_5	
	25/11/1964
201.75	
	13/9/1965
200.28_5	
	9/7/1966
15.98_5	
	25/7/1966
180.05	
	21/1/1967
60.17_5	
	22/3/1967
3.65	
	26/3/1967
56.13	
	22/5/1967
171.80_5	
	8/11/1967
27.63	
	6/12/1967
410.12	
	29/1/1969
4.01	
	2/2/1969

Y

Dates	Intervals
14/4/1903	
	9005.21
8/12/1927	
	3839.40
14/6/1938	
	3564.41
17/3/1948	
	2025.62
2/10/1953	
	3167.85
6/6/1962	
	3.95
10/6/1962	
	8.05
18/6/1962	
	3.70
21/6/1962	
	8.31_5
30/6/1962	
	3.78_5
3/7/1962	
	875.06
24/11/1964	
	11.94
6/12/1964	
	239.78
3/8/1965	
	35.94
8/9/1965	
	3.99_5
12/9/1965	
	303.12
12/7/1966	
	12.05
24/7/1966	
	208.16
18/2/1967	
	28.01_5
17/3/1967	
	3.76_5
21/3/1967	
	36.38
27/4/1967	
	11.63
8/5/1967	
	3.98_5
12/5/1967	
	4.11
17/5/1967	
	27.94
14/6/1967	
	151.70
11/11/1967	
	430.97_5
16/1/1969	
	16.06
1/2/1969	

The intervals are given in days and decimal fractions of days. The observations of 1903 and 1926 are from sketches by Lowell and Danjon. Those of 1927 are from photos taken at Lick Observatory and those of 1938 were taken at Lowell Observatory whereas those photos made in 1948 (Dollfus) and 1953 (Camichel) were taken at the Pic du Midi Observatory. The subsequent observations were, for the most part, taken from photos made at Brazzaville (Boyer) and Pic du Midi (Boyer, Guerin, Camichel). Some observations recently made both in the United States and France (Viscardy) have been added to the listing.

For each one of the photos of 1966 and 1967 it was possible, knowing the instantaneous speed of rotation, to compute the precise time of transit of the Y or Psi spot across the subsolar point. During the other elongations, on the other hand, the computation of this time of transit was carried out by extrapolation beginning from coordinates measured on the best photo of each day and based on an instantaneous equatorial speed of -- 110 m/s (1 revolution in 4 days). The intervals between the dates of transits across the subsolar point by a same formation -- Y or Psi -- were then computed by the difference method. These intervals are given in Table 2 in Julian days and Julian fractions of days. Thus, the Y spot, passing over the subsolar point on 8 September 1965, again passes over it 3.995 days later or on 12 September.

It will be noted that all of the observations are listed in chronological order. In order to avoid an arbitrary distortion of the data available, each observation was only used once with the preceding one and once with the following one.

a. When the interval between two transits is close to 4 days, it supplies directly the period of rotation for one revolution. The values obtained can in this case show considerable dispersion:

Intervals		Periods of rotation (in days)
6/6 to 10/6/62	(Y)	3.95
18/6 to 21/6/62	(Y)	3.70
30/6 to 3/7/62	(Y)	3.78_5
8/9 to 12/9/65	(Y)	3.99_5
17/3 to 21/3/67	(Y)	3.76_5
22/3 to 26/3/67	(Psi)	3.65
8/5 to 12/5/67	(Y)	3.98_5
12/5 to 17/5/67	(Y)	4.11
29/1 to 2/2/69	(psi)	4.01

The average period of rotation measured for one revolution, as deduced from this table, is 3.88 days (very close to 4 days) but the maximum deviation around this value can be ± 0.23 day.

b. Intervals included between 8 and 36 days. When the interval is close to 8 days it is clearly enough to divide it by 2 so as to obtain the average period of rotation for the two corresponding consecutive revolutions. It can reasonably be assumed that when it is close to 12 days, it is allowable to divide it by 3 so as to obtain the average period for 3 revolutions and, further, when it reaches 16 days, it is allowable to divide it by 4 in order to obtain the average period for 4 consecutive revolutions. Indeed, the quotient from division by 3 would give, in this last case, an average period of 5 days and the quotient from division by 5 would give an average period of 3 days. Now, we have seen above that recurrences of 3 and 5 days are never observed for equatorial Y and Psi spots unless these two formations are confused.

Nevertheless, an indetermination appears quite quickly for the larger intervals. Thus, the quotients from division of an interval of 36 days by 8 and 10 give average periods of rotation respectively equal to 4.5 and 3.6 days, sufficiently close to 4 days so that only a slight doubt remains taking into consideration the dispersion of rotational periods measured for 1 revolution (cf. preceding paragraph).

The following method which involves no hypothesis as to the period of rotation allows revealing the existence of an average time-stable period and therefore removes the preceding indetermination.

It is sufficient to compute the quotients for each interval using the series of whole numbers (i.e., using the series of numbers of possible revolutions performed during the interval). These quotients are entered on a histogram with each one of them shown by a square. When the period of rotation of equatorial Y and Psi spots undergoes considerable fluctuations in the passage of time, the squares will be statistically distributed over the whole length of the horizontal axis of the histogram and an indetermination will appear when an attempt will be made to find out the actual number of revolutions /348 (i.e., the average period of rotation) during a given interval. When, on the contrary, the average period of rotation is stable in time, a heavy concentration of squares will be seen around this average period and the false periods will be distributed on both sides in scattered order.

Figure 4 (the top histogram) shows the result obtained. The 13 intervals used (8 to 36 days) are referred to elongations covering a period of 8 consecutive years (1962 - 1969). There may be seen a remarkable concentration of squares around the value 4 days, each one of the 13 intervals of recurrence studied having given, by division, one square and one only in the crosshatched zone. In other words, these intervals are all multiples, by a whole number, of periods very close to 4 days. The average of the 13 periods determined in this way is 3.994 days. The maximum deviation around this value reaches ± 0.14 day. It should be noted that the histogram allows no gap to appear between the periods of the Y and Psi spots.

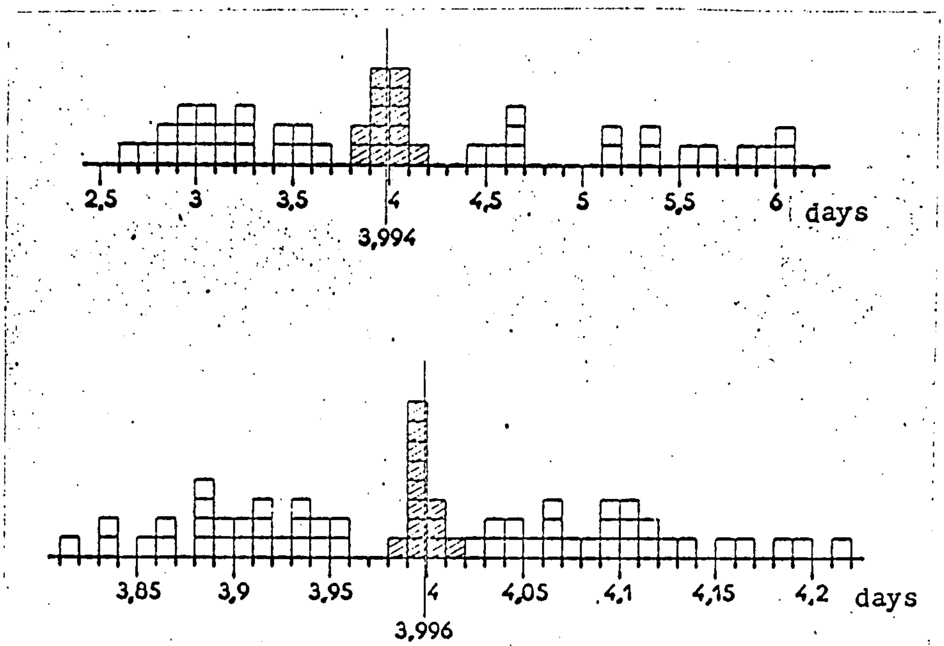

Figure 4. Histograms of the different possible periods of rotation of equatorial Y and Psi spots, computed by dividing each interval between two recurrences by the series of whole numbers. (Recurrences included between 8 and 432 days.) Each quotient is represented by a square. On both histograms there may be observed a heavy concentration of squares centered on 3.994 and 3.996 days (crosshatched areas). In these areas, each interval between two recurrences has given, through one of its quotients, one square and one only. In other words, these intervals are all multiples, by a whole number, of a period very close to 4 days, and of this period only. Everything occurs, therefore, as if an average period of rotation, stable in time, could be specified, this period being slightly less than 4 days. If the period varied appreciably from one recurrence to another, the squares would be statistically distributed over the whole length of the horizontal axis.

c. Intervals included between 56 and 432 days. Figure 4 (the bottom histogram) shows the findings obtained. The 13 intervals used are referred to elongations covering a period of 22 years (1927 - 1969). The concentration of squares around the value 4 days is still clearer than before, since each one of the 13 intervals of recurrence studied has given, as above, one square and one only in the crosshatched area. The average of the 13 periods determined in this way is 3.996 days and the maximum deviation around this value is only ± 0.01 day.

It therefore appears that the following findings can be considered as established:

a. The periods of rotation of the equatorial Y and Psi spots are the same.

b. These periods can vary appreciably from one revolution to another (± 1/4th of a day). /349

c. When the period is measured, not with one revolution but with several revolutions, the dispersion of the results obtained decreases and does so in proportion to an increase in size of the interval under consideration. In other words, even when the Y and Psi cloud formations are lost from sight for a rather long time -- either they were temporarily missing from the photos or the planet was not under observation -- they always reappear opposite the earth after an interval of time very near a whole multiple of 4 days. Everything happens, therefore, as if these formations were actually permanent ones with their temporary invisibility at the time of certain transition only being due to the interposal of underlying hazes. In spite of actual fluctuations in the time periods during which their transits were observed, the Y and Psi spots are involved, in their rotation, in a periodic process having a very great average regularity in time. This finding has been demonstrated without making any hypothesis. The measured period is 3.995 days.

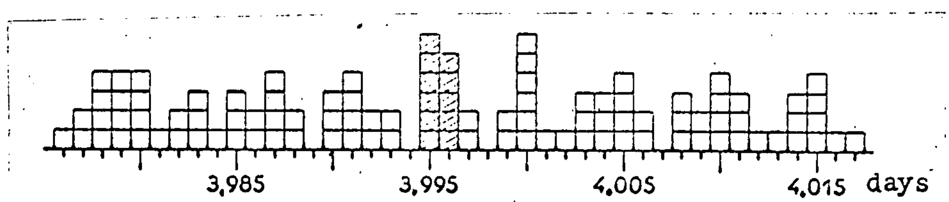

Figure 5. Histograms of the different possible periods of rotation of the equatorial Y and Psi spots for the very great time intervals (875 to 9005 days). Refer to the legend for Figure 4.

d. Intervals included between 875 and 9005 days. For some simple material reasons, the 11 intervals available were only divided by whole numbers giving quotients which are quite close to 4 days (histogram of Figure 5). /350
The results obtained appear, at first sight, to be less conclusive than before owing more particularly to the existence of a large secondary peak at 4 days which is probably a harmonic. The crosshatched area in each one of the intervals of recurrence showed, as before, one square and one only, and gave an

average period of 3.995_4 days agreeing quite well with the value given above. However, the last decimal place in this number probably has no physical significance.

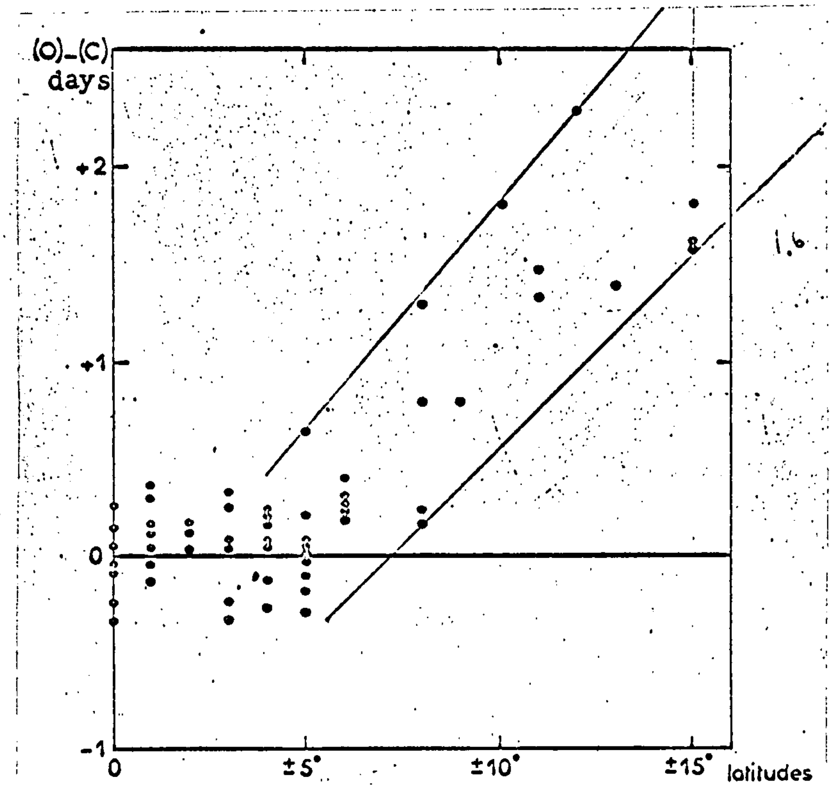

Figure 6. Comparison between the dates of the observed transits of the observed transits of the Y and Psi spots across the subsolar meridian and the dates calculated according to the ephemeris being based on a period of rotation equal to 3.995 days. As abscissa: the latitude of the point of intersection of the three branches of the Y or Psi.

Variation of Rotational Speed with Latitude

By taking as origin the transit across the subsolar point by the Y spot observed on 8 September 1965 and by taking as a basis one period of synodic rotation of equatorial Y and Psi spots equal to 3.995 days, we have established an ephemeris giving in days and fractions of a day, with 4 decimal places, the dates of transit of the center of these spots across the subsolar meridian for the period included between August 1948 and December 1970. By comparing these computed dates (C) with the dates actually observed up until this day (O), and by plotting on a graph the deviations (O) - (C) as a function of the latitude of the reference point measured, we have been able to confirm the excellent agreement between the ephemeris and the observations so long as the latitude of the reference point does not exceed 6°. On the other hand, in the case of the high latitudes, a systematic deviation appears with a positive sign. This deviation increases with latitude reaching almost 2 days when the center of the Y or Psi spot is located at ± 15° from the equator (Figure 6).

Everything takes place, therefore, as if the upper cloud atmosphere of Venus was not rotating as one unit. Not only the highest layers (at whose level the changing spots are probably located) appear to rotate more quickly than the lower layers supporting the Y and Psi spot, but again the period of rotation of these lower layers increases from the equatorial zone (where it is close to 4 days) towards the tropical regions. The Y and Psi spots are behind according to the ephemeris from the moment they deviate from the equator by more than 6°.[2]

Conclusion

New observations will clearly be necessary in order to specify and supplement the various points discussed in this study.

It would first of all be advisable to compile the dates of transit of the Y and Psi spots across the subsolar meridian during the years to come and to compare these dates with those supplied by our ephemeris set up on the basis of a synodic period of 3.995 days. Here, by way of illustration (Table 3), is an extract from this ephemeris for the year 1970. The dates predicted for the transits of the point of intersection of the three branches of the Y across the subsolar point are shown in days and fractions of a day. It is enough to add 1 in order to obtain approximately the dates of the transits of the Psi spot. This data can only be applied, bear this in mind, to reference points located on the equator or no more than a maximum of ± 6° from the latter.

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2. The discovery of this differential equation could explain a phenomenon previously observed by one of us and which had been described as a variation of the period of atmospheric rotation following a 104 day cycle. Indeed, when we draw up a list of the Y and Psi spots farthest from the equator, we ascertain that the dates of their appearances are separated by very close time intervals in whole multiples of 104 days. Thus, this period is probably not that of a variation in time of the speed of atmospheric rotation but that of the cycle of variations in latitude of the Y and Psi spots.

Only the accumulation, in the course of the coming years, of many high-quality photos will allow demonstration of any long-term modification of the average speed of equatorial rotation of the Y and Psi spots as well as specification of the cycle of variations in latitude of these formations and the laws governing their instantaneous diurnal motion.

The basic problem, still not solved, remains that of the origin of the swift retrograde rotation of the Venusian atmosphere around a sphere with an extremely slow retrograde rotation. Computational and design models will have to be prepared by the theorists for the purpose of taking the observations into account. Perhaps the great average regularity of this rotation can be explained by the enormous inertia of the atmospheric mass in motion provided this motion is maintained by a thermal machine effect created by solar heating. /351

Allowing for the present state of the art, there is, however, one point which is beyond, it would appear, our understanding. This point concerns the permanency of the Y and Psi formations in an atmosphere which does not rotate as one unit and which is necessarily stirred up by convectional currents.

TABLE 3. DATES OF THE PASSAGE OF THE Y EQUATORIAL SUBSOLAR POINT
1970

January	March	May	July	September	November
3.297	4.225	3.152	2.080	4.002	2.930
7.292	8.220	7.147	6.075	7.998	6.925
11.287	12.215	11.142	10.070	11.993	10.920
15.283	16.210	15.138	14.065	15.988	14.915
19.278	20.205	19.133	18.060	19.983	18.911
23.273	24.200	23.128	22.056	23.978	22.906
27.268	28.196	27.123	26.051	27.973	26.901
31.263		31.118	30.046		30.896
February	**April**	**June**	**August**	**October**	**December**
4.258	1.191	4.114	3.041	1.969	4.891
8.254	5.186	8.109	7.036	5.964	8.886
12.249	9.181	12.104	11.031	9.959	12.882
16.244	13.176	16.099	15.027	13.954	16.877
20.239	17.171	20.094	19.022	17.949	20.872
24.234	21.167	24.089	23.017	21.944	24.867
28.229	25.162	28.085	27.012	25.940	28.862
	29.157		31.007	29.935	32.858

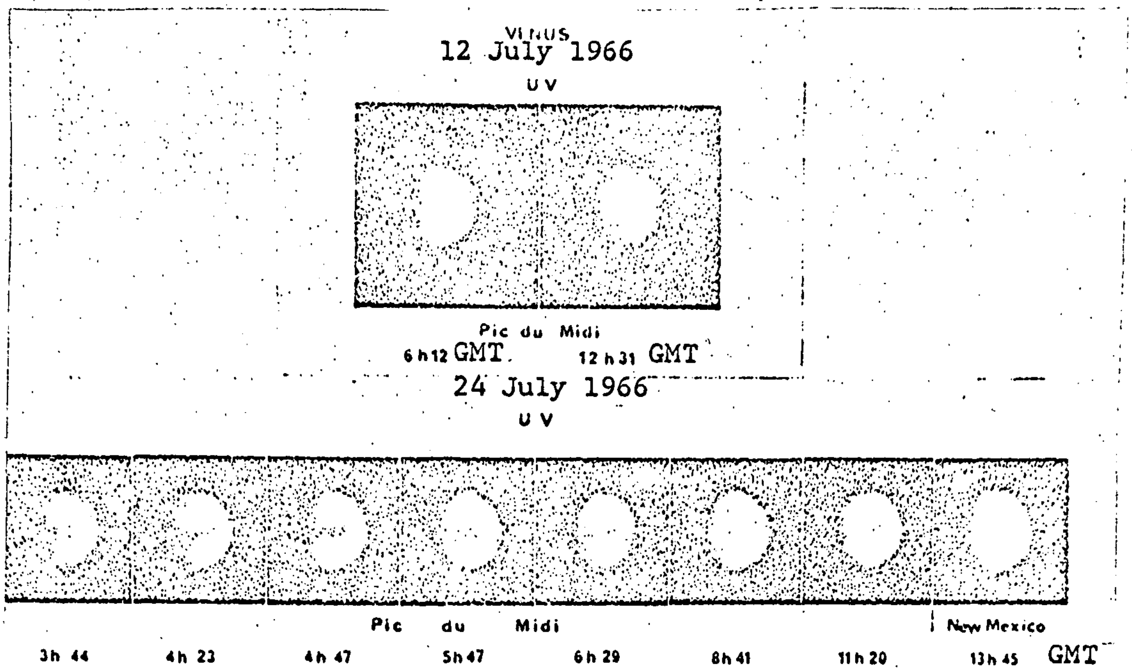

Plate I. The rotation of the Y seen on two occasions, 12 and 24 July 1966. (South is at the top.) The series of 24 July extends over 10 hours at one time and shows the progressive movement of the formation towards the limb. The speeds of equatorial rotation measured with these two series are respectively equal at -92 and -88 m/s.

When it was possible, the best images from each series were made into a composite. The reproductions provided by us here were obtained by using the technique of masking under the enlarger by shaking a curvilinear screen producing a degraded shadow in such a manner as to make up for the heavy darkening of the planet at the terminator. This technique is necessary if it is desired to cause total appearance of the spots with a high contrast over the whole extent of the visible part of Venus for the purpose of photomechanical reproduction. It has likewise been used for the images of plates II, III and IV. On the other hand, the measurements of the speeds of instantaneous rotation were made on non-masked positive prints produced with low-contrast photographic paper as stated in the text of the article.

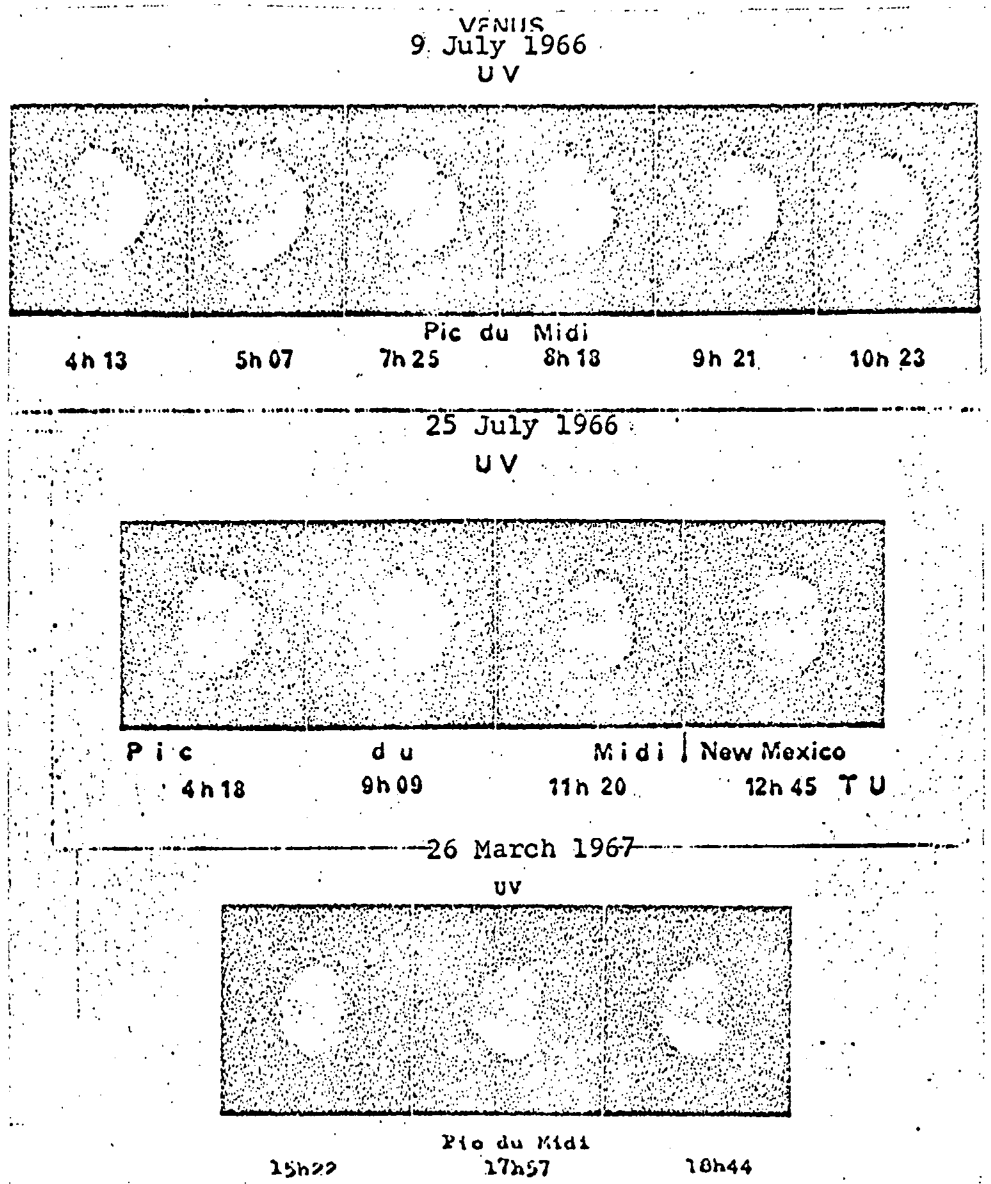

Plate II. The rotation of the Psi, observed on three occasions 9 and 25 July 1966 and 26 March 1967. (South is at the top.) On the series of 9 July, the northern branch of the Psi is hazy and the movement of the formation is carried out according to a trajectory slightly inclined to the north with respect to the equator. The equatorial speed is equal to -98 m/s. On the series of 25 July 1966 (equatorial speed: -68 m/s) and 26 March 1957, the Psi is not hazy.

354

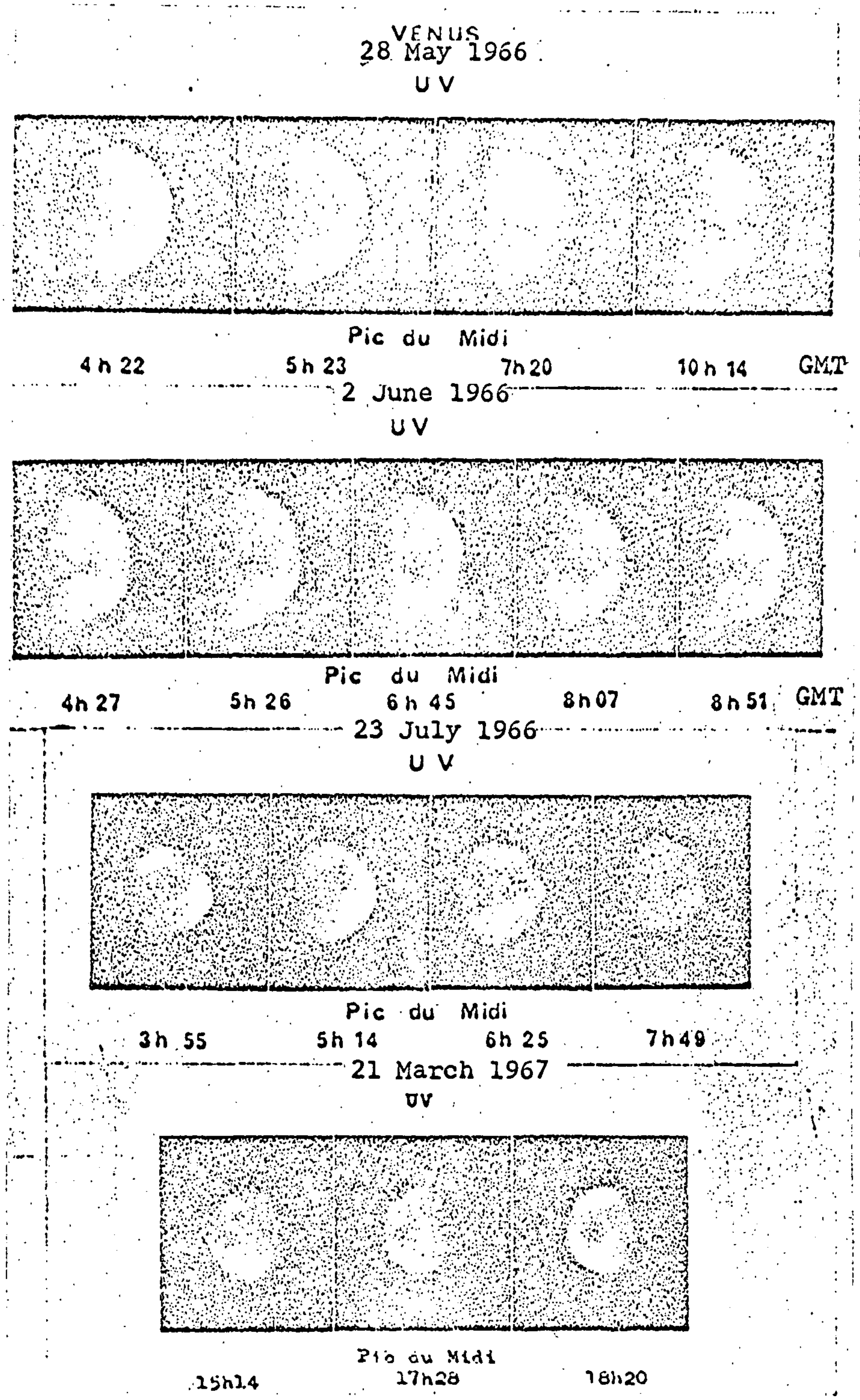

Plate III. Four series showing the continuous rotation of the cloud spots of Venus. (South is at the top.) On 28 May and 2 June 1966, the spots photographed do not correspond to permanent configurations. The spot visible on 28 May rotates at an equatorial speed of -96 m/s without being appreciably deformed. On 2 June, to the contrary, the dark equatorial nodosity is subject to variations in shape between the beginning and end of the series and the speed of rotation, more difficult to measure is equal to -108 m/s. On 23 July 1966 the photographic spots appear to resemble an H (cf. Plate V) but the latter is considerably offset in latitude towards the south. Its speed of rotation is swift: -157 m/s. Finally, on 21 March 1967, the Y can be seen. It is, however, partially hidden and the large dark nodosity located at the intersection of the three branches of the letter revolves rapidly: -133 m/s.

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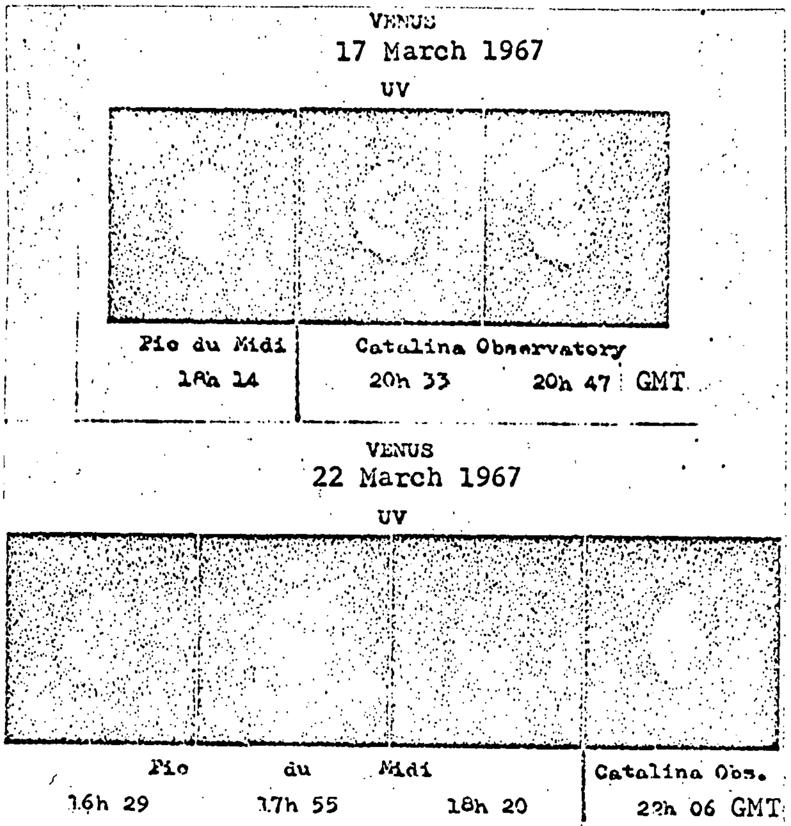

Plate IV. Transits of the swift moving Y and Psi-shaped cloud spots. (South is at the top.) On 17 March 1967 at 1814 hrs, the central regions and the southern branch of the Y are concealed. They are revealed again at 2033 hrs and the Y is seen in its conventional shape at 2047 hrs. The Y again reappears opposite the earth 4 days later on 21 March (Plate III, bottom images). The following day, on 22 March, the Psi is invisible from 1629 hrs to 1820 hrs. A dark spot covers it and is moving very quickly towards the terminator in the retrograde direction. At 2206 hrs this spot has disappeared and the Psi, partly cleared up, appears consistent with the predictions of the ephemeris.

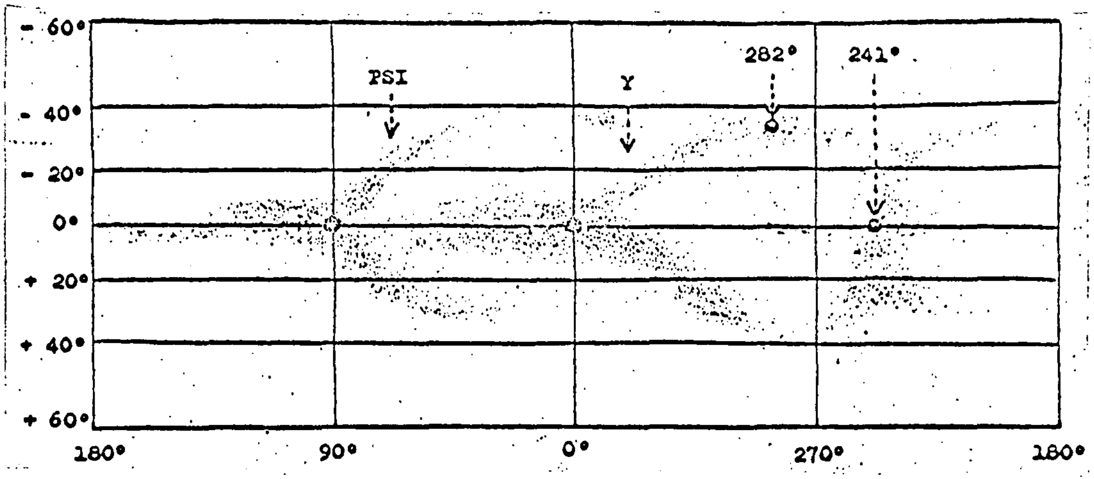

Plate V. Synoptic map of the recurrent configurations of the outer cloud layers of Venus. South is at the bottom. The origin of the longitudes is the point of intersection of the three branches of the horizontal Y.

REFERENCES

1. Boyer, Ch., Camichel, H., "Photographic Observations of the Planet Venus," Annal. Astrophys., 24, 1961, pp. 531-535. /351

2. Boyer, Ch., "Investigations on the Rotation of Venus," L'Astronomie, 1965, pp. 223-228.

3. Boyer, Ch., Guerin, P., "Direct Proof by Photography of a Retrograde Rotation of Venus in 4 Days," Compt. Rend. Acad. Sc., 263, 1966, pp. 253-255.

4. Boyer, Ch., Camichel, H., "Determination of the Rotational Speed of the Spots of Venus," Compt. Rend. Acad. Sc., 264, 1967, pp. 990-992.

5. Dollfus, A., "Synthesis on the Ultraviolet Survey of Clouds in Venus' Atmosphere," In The Atmospheres of Venus and Mars, Gordon and Breach, 1968, pp. 133-145.

6. Guerin, P., Planetes et Satellites [Planets and Satellites], Larousse, Paris, 1967, p. 174.

7. Guerin, P., Thirteenth General Assembly of the IAU, Commission 16, Report, 1967.

8. Lowell Observatory Bulletin No. 6, 1903-1911, p. 160.

9. Guinot, B., Feissel, M., "Spectrographic Measurement of Movements in the Atmosphere of Venus," Jl des Obs., 51, 1968, pp. 13-20.

10. Rudaux, L., L'Astronomie [Astronomy], 1929, p. 183.

11. Smith, B. A., "Rotation of Venus: Continuing Contradictions," Science, 158, 1967, pp. 114-116.

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